A high frequency sensor for optical beam deflection atomic force microscopy

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We demonstrate a novel electronic readout for quadrant photodiode based optical beam deflection setups. In our readout, the signals used to calculate the deflections remain as currents, instead of undergoing an immediate conversion to voltages. Bipolar current mirrors are used to perform all mathematical operations at the transistor level, including the signal normalizing division. This method has numerous advantages, leading to significantly simpler designs that avoid large voltage swings and parasitic capacitances. The bandwidth of our readout is solely limited by the capacitance of the quadrant photodiode junctions, making the effective bandwidth a function of the intensity of photocurrents and thus the applied power of the beam deflection laser. Using commercially available components and laser intensities of 1–4 mW we achieved a 3 dB bandwidth of 20 MHz with deflection sensitivities of up to 0.5–1 V/nm and deflection noise levels below 4.5 fm/√Hz. Atomic resolution imaging of muscovite mica using FM–AFM in water demonstrates the sensitivity of this novel readout.


I. INTRODUCTION

Small dimension cantilevers remain an unexplored opportunity in AFM. Decreasing cantilever dimensions will increase resonance frequencies without changing spring constants, allowing faster measurements without a decrease in sensitivity in ambient environments. This is useful for true atomic resolution scanning, studying the dynamic behavior of biological macromolecules, high speed AFM scanning, and high sensitivity mass sensors. However, use of these small dimensional cantilevers has generally been limited by instrumentation. Optical beam deflection sensors on commercial microscopes have limited bandwidths predominately due to the design of the electronic readouts. Small cantilevers with resonance frequencies beyond a few megahertz have been measured in the past through interferometry or by using heterodyne down-sampling methods, however, it has not been possible to measure these oscillations directly using beam deflection. Therefore, it is an ongoing interest in AFM to improve the bandwidth of beam deflection sensors. In this article, we report on a new, low noise, high bandwidth quadrant photodiode deflection sensor based on translinear bipolar junction transitors (BJT) capable of detecting signals in excess of 20 MHz.

Thermal Brownian motion of the cantilever sets the limit for the smallest drivable eigenmode amplitudes and smallest detectable forces. Sensitivity increases through reductions in the smallest drivable oscillation amplitudes by using smaller cantilevers and thus higher oscillation frequencies remain desirable. However, due to the limitations of readout instrumentation, the dimension reduction and frequency boosting of cantilevers has been slow. Recent developments in AFM instrumentation focus on improving the optical system as well as the bandwidth and noise of the quadrant photodiode deflection sensor. These improvements increase the signal-to-noise ratio (SNR) while simultaneously opening the possibility of using small cantilevers for high resolution scanning, and will help decrease the gap that remains between the experimental and theoretical lower limits of detectable deflection.

Several scanning probe force detection systems are successfully used today with considerably different force detection sensitivities. These include the piezoelectric force sensors, interferometric sensors, and the optical beam deflection sensors (OBDs). An analysis of the sensitivities reported to date is shown in Table I, including the resonance frequencies at which these sensitivities were measured.

Any well designed detection system will eventually reach the shot noise of the electro-optical system as the lowest possible noise floor. Maintaining this noise floor is crucial for high resolution imaging, particularly for low-Q environments. When designing OBD readouts for use with smaller cantilevers, it becomes increasingly difficult not only to achieve the necessary bandwidth, but also to maintain the shot noise level as a noise floor.

Most commercial optical beam deflection sensors used in AFM today are based on bicell or quadrant photodiodes. When a laser or any other source of light is focused on the sensor, the arithmetic difference between the photocurrents of the upper and lower diode(s) is used as a measure of the vertical position of the incident light, termed vertical deflection. To our knowledge, in all commercially available AFM setups the signal currents from each quadrant are individually amplified and converted to a voltage, which is then further processed using voltage-mode arithmetic circuits to yield...
the vertical deflection. With today’s state of the art components, such readouts can reach bandwidths up to several megahertz.25

Circuits where the relevant signals are represented by currents, rather than voltages, have numerous advantages, including the realization of designs with a reduced number of components, a reduction in power consumption, and the avoidance of large voltage swings and thus parasitic capacitances, which will give significant improvements in the bandwidth.27 Such current-mode circuit designs are known as translinear circuits; this class of circuits primarily uses bipolar transistors operating below the threshold to conduct mathematical operations on currents. Here we demonstrate that the signal currents can be directly subtracted from one another using Kirchhoff’s current law, and only the differential currents are amplified and extracted, which yields the same vertical deflection signal. We demonstrate that significant improvements in bandwidth and noise are achieved when switching to such a readout method. The use of currents as the relevant signal in OBD has been attempted in the past,28 but was implemented using multiple photodiodes; a similar solution does not exist for the common quadrant photodiode used in the vast majority of AFMs today.

II. PRINCIPLE OF THE TRANSLINEAR BEAM DEFLECTION SENSOR

A. Adding and subtracting currents

Characteristic for each photodiode is the junction capacitance of the photodiode and the current produced by the exposure to light; the relevant signal extracted from a photodiode is an intensity-dependent current. The equivalent model of a typical quadrant photodiode is shown in Fig. 1(a). The quadrant photodiode device has four anodes, each with the signal current relative to the light corresponding to its quadrant, and one cathode, common to all diodes. The common cathode design of the quadrant and bicell photodiodes prohibits the direct connection of anode-to-cathode, i.e., the diodes cannot simply be placed in parallel in order to compute the deflection. Our novel optical deflection readout overcomes this limitation by using current mirrors, an active device designed to output a duplicated input current (regardless of the load), and a fundamental building block of translinear circuits. By copying the currents originating from each anode, the signal currents can be separated from the common cathode, and solely

![Image](https://example.com/image.png)
the differential currents can be amplified and extracted. The simplest design, a current subtracter, was proposed by Rosenthal in Ref. 29 and is detailed in Fig. 1(b). The heart of the current subtracter is the current mirror.

In the design of Fig. 1(c), each initial quadrant diode current is copied using bipolar NPN transistors, similar to the adjacent quadrants are added together, and then subtracted from the currents originating from the other two adjacent quadrants. For example, the copied current of quadrant A \(i_{A}\) is added to the copied current of the adjacent quadrant \(B \left( i_{B} \right) \) on node X, and their sum is sourced from the diode-connected transistor of a bipolar PNP current mirror. The PNP mirror copies the current from node X and sinks it to node Y, from which the copied currents of \(C \left( i_{C} \right) \) and \(D \left( i_{D} \right) \) source their respective currents. Any imbalance in the currents on node Y is either sourced or sunk through the transimpedance amplifier, yielding an effective vertical deflection, similar to the current subtractor shown in Fig. 1(b).

B. Extracting the sum

In the circuit of Fig. 1(c), the currents originating from the four quadrants of the photodiode are gathered and inserted into the current mirror made up of transistors Q13 and Q14. The collector of Q14 feeds the second transimpedance amplifier, resulting in a sum signal. An alternative method to quantify the sum would be to mirror the current running through the cathode of the quadrant photodiode.

C. Signal normalization and amplification

In many AFMs, laser intensity fluctuations can be a significant and unnecessary source of noise. Intensity fluctuations are common to all quadrants the laser falls upon, and thus common to each photocurrent. In many optical readouts the vertical and horizontal deflection signals are subsequently divided by the sum signal (or common mode rejection using instrumentation amplifiers), removing the intensity fluctuations and other common noise entirely. The relatively slow analog dividers or instrumentation amplifiers used will again significantly reduce the bandwidth. In our setup, we use a translinear normalizer [which is created when transistors Q11 and Q12 are added as shown in the dotted box of Fig. 1(c)]. It is noteworthy that this normalization method is very fast, limited only by the bandwidth of the transistors. This overcomes the significant bandwidth bottleneck mentioned previously. In addition to removing common mode signals from all four photodiode currents, the translinear normalizer causes a nonunity current ratio in the mirrored currents by the externally applied input current \(i_{\text{ref}}\), which can be an order of magnitude larger than the photocurrents, depending on the transistors used. This introduces a large transistor level gain, in which small differential currents are significantly amplified before the signal is further buffered by the transimpedance stage. Active control of this current will allow the user to adjust the desired amplitude regime (small amplitudes <1 nm or larger amplitudes >20 nm), without the need of exchanging any hardware. Thus, a complete single channel beam deflection sensor requires only 14 bipolar transistors and 2 transimpedance stages.

D. Noise considerations

Every amplifier will add its own noise to an input signal; translinear circuits offer no exception. This reduction in SNR caused by the internal shot and thermal noises of an amplifier is termed noise factor (or noise figure) and quantifies the drop in SNR when the signal passes through the stage under normal operating conditions. When multiple stages are cascaded in series, the noise factor of each individual stage will propagate the noise according to Friis’s formula for electronic noise:

\[
nf_{\text{tot}} = nf_1 + \frac{nf_2 - 1}{G_1} + \ldots + \frac{nf_N - 1}{G_1G_2\ldots G_N},
\]

where \(nf_N\) is the noise factor of the respective cascaded stage and \(G_N\) is the gain of that stage. Thus, a strong gain in an early stage will significantly reduce the noise contributions of all subsequent stages.

The initial amplification of the photodiode signals takes place in the primary current mirrors [Q1–Q8 in Fig. 1(c)]. Noise analysis of BJT current mirrors has been done in the past; the most predominant sources are shot noise due to the current flow of carriers in the base and collector and the thermal noise of the base resistance, termed limiting noise, and the frequency dependent flicker noise inherent to most electronic devices, termed excess noise. The unity gain spectral output current noise of a typical BJT current mirror is given as

\[
N_o^2 = 2I_{\text{cs}}^2(1 + 2b + b^2/\beta) + I_{\text{bx}}^2(1 + (mb)^2) / (1 + b/\beta)^2,
\]

where \(I_{\text{cs}}\) is the spectral collector current noise, \(I_{\text{bx}}\) is the spectral base current noise, \(m\) is a constant detailing the intensity of the excess noise, \(\beta\) is the small signal current gain, and \(b\) is the normalized intrinsic base resistance. Thus, the noise factor of the device is then given as

\[
f = \sqrt{1 + \frac{N_o^2}{N_i^2}},
\]

where \(N_i\) is the equivalent input noise. When a device has a defined input impedance, the input is normally connected to a sensor with an equal output impedance in order to maximize the signal power transfer. Thus, the noise can never be lower than the thermal noise of a resistor with the same impedance, given as \(\sqrt{2k_BT/R}\). With knowledge of transistor characteristics and input impedances, the noise factor of a current mirror can be calculated.

The current mirror of the divider transistors [Q11 and Q12, Fig. 1(c)] is cascaded with the primary current mirrors of each channel. Thus, the noise generated by the divider will add directly to the total noise of the system as given by Friis’s formula. Setting the primary current mirrors to unity gain is...
the worst case scenario, as noise propagation is at maximum. By increasing the primary transistor’s gain by adjusting the reference current $i_{ref}$, the noise caused by the divider and all subsequent stages is significantly reduced and the SNR is increased.

E. Dual channel translinear readout

In the dual channel design [Fig. 1(d)], the current from each anode is copied twice using multiple output current mirrors,\(^3\) once each for the horizontal and vertical calculations. As more transistors are added to the current mirrors, the base currents will increasingly drain and distort the photodiode input current. Furthermore, the base-emitter capacitance of each new transistor indirectly adds to the junction capacitance of the photodiode, which will reduce the bandwidth. In order to bypass these problems, beta helper transistors Q1–Q4 are added, effectively reducing the base-emitter capacitive loads on the photocurrents. Ground connected resistors R1 and R2 serve to set the transistor level gain $i_{out}$ of the translinear normalizer on the horizontal and vertical channels, respectively.

III. IMPLEMENTATION

A. Components

The single and dual channel circuits were implemented with discrete components, and consisted of the following parts: the quadrant photodiode used was a SD 085-23-21-021 by Advanced Photonix; HFA3127 and HFA3128 by Intersil for the NPN and PNP transistors; the resistors governing $i_{out}$ [R1 and R2 in Fig. 1(d)] were adjustable potentiometers between 10–500Ω, and the transimpedance feedback resistors were 5.6 kΩ. The feedback capacitors (transimpedance feedback capacitors, not shown in Fig. 1) were set at 2 pF. The operational amplifiers used were THS4011. +V was adjustable from 1.2 to 4 V and –V was –3.5 V; the transimpedance stages were powered with ±12 V.

B. Bandwidth measurements using emulated photodiodes

In order to measure the electronic bandwidth of the system, the photodiodes were emulated by using a high bandwidth current source with a linear frequency response in the region of interest. In addition, adding capacitances in parallel to the “ideal” current source brought the setup closer to the true operation of a photodiode. This excitation circuit can be seen in Fig. 2(a). Capacitors of 10 pF were used, as these were close to the manufacturer stated junction capacitance (9 pF) of the quadrant photodiode when properly reverse biased. A vertical deflection was simulated by applying an oscillating current signal to the quadrants A and B, and applying the same 180° phase shifted signal to quadrants C and D. The bandwidth of the current source, consisting primarily of an AD8132 differential output amplifier, was well over 50 MHz (tested separately). The AD8132 allows the application of a dc offset with an added ac signal, which was necessary for simulating the true operating nature of a quadrant photodiode. The bandwidth of the combined excitation circuit and readout was analyzed using a network analyzer (Hewlett Packard 8753E with 41802A 1 MΩ terminated input adapter). Figure 2(b) shows that as we increase the current, which corresponds to an increase in the photocurrent due to the increasing laser intensity, the bandwidth of the system will increase as well, up to 20 MHz. This is due to the photodiode junction capacitances charging more rapidly due to the increasing photocurrent. When total currents (sum of all quadrants) are below 1 mA,\(^3\) the bandwidth is limited by the junction capacitance of the quadrant photodiodes, as the bipolar transistors chosen have significantly larger bandwidths. At higher intensities, the transimpedance stage assumes the role of limiting factor. Care must be taken to minimize the resistance of a line connecting any two transistors, as this will quickly increase the voltage swing along the lines, degrading the bandwidth performance. Our SPICE simulations suggest that the bandwidth can be increased to over 70 MHz through the use of smaller quadrant photodiodes and faster transimpedance stage amplifiers without a significant reduction in signal-to-noise. Additionally, it has been shown both theoretically and experimentally\(^7\),\(^3\) that the shot noise floor decreases as the laser intensity is further increased. With regard to electronics, it would be desirable to have the brightest possible light source, as long as the optical noise in the light source remains shot noise limited.
IV. APPLICATION

A. Bandwidth and noise measurements of selected high frequency cantilevers

In order to accurately measure the response of the deflection sensor with small dimension high frequency cantilevers, an optical tabletop OBD setup was designed with photothermal excitation capability. The diameter of the laser spot on the backside of the cantilever was measured to be less than 4 μm. The frequency response of a prototype USNMCB cantilever (Nanosensors, Neuchatel, Switzerland) can be seen in Fig. 3(a). The amplitude and phase versus frequency curves of the first and second eigenmodes of a 3.5 MHz prototype cantilever are seen in Figs. 3(b) and 3(c), respectively.

In addition to the bandwidth, the noise floor was measured. For both imaging and noise analysis, the circuit was attached to a modified multimode (Digital Instruments) head in combination with an E-scanner and a Nanonis (SPECs, Berlin, Germany) controller. The microscope was enclosed in a home-built acoustic and electric shield on a vibration isolation table. The optical lever sensitivity of an Arrow UHF (Nanoworld, Neuchâtel, Switzerland) was calibrated by a surface approach measurement in which the amplitude of the first eigenmode is recorded against the tip sample distance. By increasing the translinear normalizer reference current \( i_{\text{ref}} \) [Fig. 1(c)], we can significantly increase the signal gain, and through this the optical lever sensitivity. When increasing this current to high values (a few mA), sensitivities are around 0.5–1 V/nm and noise levels are around 4.5 fm/√Hz, as can be seen in Fig. 3(d).

B. DC stability

In addition to the large bandwidth, the system provides very high stability and sensitivity at dc as well. In order to measure these effects at dc, an Arrow UHF cantilever was mounted in the microscope which was enclosed in the acoustic and electric shield and was allowed to stabilize thermally for 5 h before the measurement. The dc sensitivity of the beam deflection was measured to be 1.046 V/nm. In a time interval of 5 s (sampling rate 20 ms), the RMS noise in the vertical deflection was recorded as 3.145 mV (15.493 mV peak to peak). In a time interval of 5 min (sampling rate 484 ms), the RMS noise jumped to 9.293 mV (53.790 mV peak to peak). Finally over an interval of 5 h (sampling rate 5 s), the RMS noise was recorded as 20.947 mV (106.913 mV peak to peak).

C. Atomic resolution imaging

Figure 4 shows a high resolution FM–AFM image of muscovite mica measured in 150 mM KCl and 20 mM tris-HCl made using 18.2 MΩ deionized water. The sample was mechanically cleaved numerous times shortly before scanning. Atomic scale contrast can clearly be seen, confirming that the developed deflection sensor is capable of very high resolution scanning.
V. CONCLUSION

We demonstrated the concept and practical realization of a new electronic design for position sensitive photodiode readouts. The novelty is that the main arithmetic operations to extract and normalize the vertical deflection are performed using currents on the transistor level. In order to test the performance of our circuit we replaced the quadrant photodiode by an equivalent but external current source and demonstrated that bandwidths above 20 MHz can be achieved. This result is confirmed in an OBD setup, where the first and second flexural eigenmodes of ultrashort cantilevers could be detected at frequencies of 3.5 and 21.4 MHz. From the thermal noise we extracted a spectral noise density of 4.5 fm/√Hz. Such low noise levels permit atomic resolution imaging of muscovite mica in liquid, which clearly demonstrates the potential of our new readout electronics.

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35Using a 650 nm laser, 1 mA is approximately equal to a laser intensity of 2.5 mW. This is dependent on the photodiode responsivity and the laser wavelength chosen.